Using Full Spectrum Plots

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Full Spectrum plots have recently received a lot of worldwide attention. In addition to the work being done at Bently Rotor Dynamics Research Corporation and Bently Nevada Corporation, there is some related work ("Directional Power Spectrum"[Ref. 1]and "Holo Spectrum"[Ref. 2]) being done in Korea and the People's Republic of China. This article discusses the benefits of Full Spectra and how to use Full Spectrum plots in a machinery diagnostic analysis for fluid-induced instabilities. In Part 2, in the next issue, I will discuss using Full Spectrum plots in machinery diagnostic analyses for rubs, preloads and misalignment, shaft cracks and split criticals.

Briefly, a Full Spectrum has the same relationship to a "standard" Spectrum in the frequency domain as an Orbit has to a Timebase waveform in the time domain. While a Spectrum and a Timebase waveform only require a single input, a Full Spectrum and an Orbit both require signals from two orthogonal sources [Ref. 3]. This provides both Orbits [Ref. 4] and Full Spectra with information on the ellipticity of the orbit and the direction of vibration, something neither a Spectrum nor a Timebase waveform has. From the direction of vibration, if the direction of shaft rotation is known, the vibration precession can be determined. Orbit ellipticity and vibration precession are two of the basic characteristics which must be determined before a comprehensive machinery diagnostic analysis can be made.

Conducting a correct and comprehensive machinery diagnostic analysis is a very difficult proposition. Different techniques and data formats provide the analyst with different "tools" with which to work. The more tools the analyst has available and knows how to use, the easier this difficult job becomes. Sometimes one tool provides the best insight while another tool may be best for a different situation. I like to use the analogy of automobile mechanics: the professional has a full tool chest and a significant amount of training on when and how to use each tool. The amateur may only have a crescent wrench, a screwdriver and a lot of good intentions.

The purposes of this article are threefold:

(1) To define the conventions used for Full Spectrum plots .

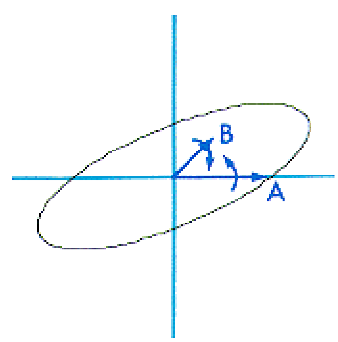
(2) To show how to extract information from a Full Spectrum plot (note that a Full Spectrum plot, in and of itself, is nothing more than processed data which may or may not contain any information. Data, even processed data, is nothing more than a set of numbers, whereas information increases our knowledge or provides answers to questions.)

(3) To briefly show how this information is used in a machinery diagnostic strategy to provide answers to the fundamental questions, "What is my machine doing?" and "Why is it doing that?"

Generating an ellipse with rotating vectors

As illustrated, but not explained, in my introductory article on Full Spectrum in the June 1993 Orbit [Ref. 3], a single frequency elliptical Orbit can be constructed from forward and reverse vibration components. If vectors $\vec{A}$ and $\vec{B}$ rotate in opposite directions at the same frequency, their vector sum describes an ellipse. The ellipticity and precession of the Orbit depends on the amplitude relationship between $\vec{A}$ and $\vec{B}$. The orientation of the major axis of the ellipse depends on the phase relationship between $\vec{A}$ and $\vec{B}$. Figures 1 through 6 show some simple examples.

When dealing with machinery diagnostics and Full Spectra, the same concept is valid except in the inverse direction. **The machine is doing what**



Forward vector
$A = 3 \cos (\omega t + 0)$
Reverse vector
$B = 1.5 \cos (-\omega t + 45°)$

Figure 1

the Orbit shows it is doing; the $\overrightarrow{\mathbf{A}}$ and $\overrightarrow{\mathbf{B}}$ vectors, plotted as forward vibration and reverse vibration components, respectively, are solutions from the FFT computation which generate the same Orbit.

Conventions

Pertinent conventions are defined as follows:

(1) Rotational directions, clockwise (CW) and counterclockwise (CCW), are determined by looking from the driver end of a machine train towards the driven end, unless otherwise specified.

(2) When the direction of vibration and the direction of shaft rotation are the same, forward precession occurs. When they are opposite, reverse precession occurs.

Fluid-induced instability

A fluid-induced instability, commonly referred to as oil whirl or oil whip, is the special dual resonance condition resulting when both the Direct Dynamic Stiffness (which relates to the system mechanical resonance) and the Quadrature Dynamic Stiffness (which relates to the system fluid resonance) both equal zero at the same time. Basically, the Direct Dynamic Stiffness equals zero when the mass stiffness term and the spring stiffness term are equal and opposite each other ($K = \Omega^2 M$), leaving the Quadrature Dynamic Stiffness term as the only restraint for the system. The Quadrature Dynamic Stiffness term equals zero when $\omega = \lambda\Omega$ [Ref. 5], leaving the Direct Dynamic Stiffness term as the only restraint for the system.

Definition of terms:

M = rotor mass

K = spring stiffness

Ω = rotative speed

λ = fluid circumferential average velocity ratio

ω = angular velocity of rotor precession.

When both Direct and Quadrature Stiffnesses are zero at the same time, the system is operating on top of both its mechanical and fluid resonances at the same time, and there is no restraint for the system: the system is unstable. A new balance of forces is achieved at the limit cycle of the rotor orbital motion, i.e., when the orbital motion approaches the bearing or seal clearance.

From a machinery diagnostic point of view, the instability vibration is driven by the tangential component of the fluid wedge support force, which always acts in the direction of shaft rotation. The most definitive signal characteristics of an instability vibration are a circular (or nearly circular) Orbit with large (limit cycle) amplitude and forward precession at a frequency of approximately $\lambda\Omega$. Since the value of λ is a nonlinear function of shaft eccentricity, bearing/seal

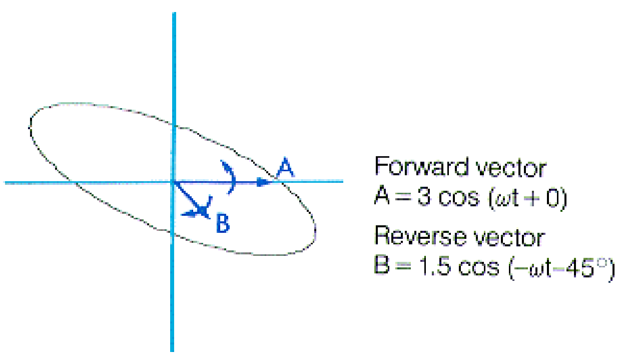


Figure 2

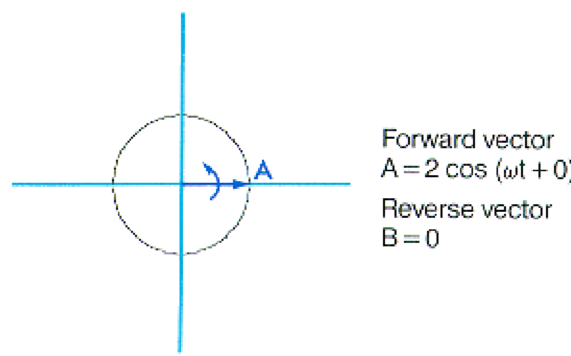


Figure 3

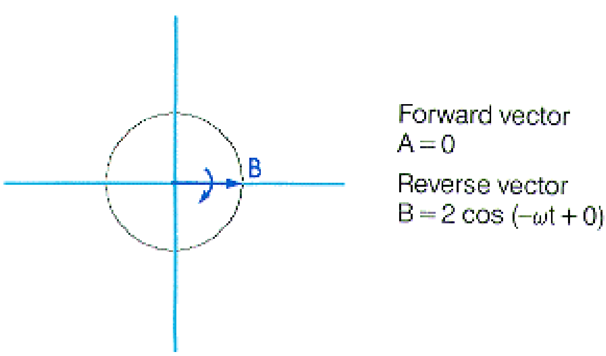


Figure 4

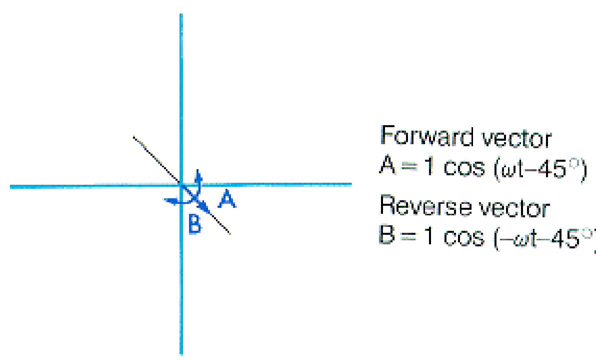


Figure 5

geometry, surface roughness, and fluid inlet conditions [Ref. 6], the frequency of the instability vibration can vary, but for typical conditions is often slightly less than ½X for whirl instabilities.

Figure 7 shows a Full Cascade plot for a startup of a CCW-rotating machine with a threshold of stability of approximately 2300 rpm. The two orthogonal (0° and 90° Right) displacement transducers were located at the outboard bearing of the machine, which is where the instability was located. Figures 8 and 9 show the corresponding Orbit/Timebase plots for both whirl (2790 rpm) and whip (4890 rpm). Note that the Orbits are both circular with high amplitudes and forward precession (the shaft is rotating counterclockwise and the horizontal motion leads the vertical motion by approximately 90°). The Full Cascade plot confirms that, for speeds less than approximately 4500 rpm, the vibration is composed almost entirely of high amplitude forward vibration components. The absence of reverse vibration components signifies that the shape of the Orbit is circular and that the precession is forward. The instability vibration frequency is approximately 0.45X for the whirl instability, and it begins to diverge when the system begins the transition into whip instability as the rotor speed approaches 5000 rpm. Also notice that the Orbit for the whip instability (Figure 9) is slightly elliptical, and the Full Spectrum plot confirms that small reverse vibration components exist for machine speeds above approximately 4500 rpm. ■

References

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5. Bently, D.E., Muszynska, A., "Fluid-generated Instabilities of Rotors," Orbit, Volume 10, No. 1, April, 1989.
6. Bently, D.E., Muszynska, A., "Role of Circumferential Flow in the Stability of Fluid-Handling Machine Rotors," The Fifth Workshop on Rotordynamics Instability Problems in High Performance Turbomachinery, Texas A&M University, College Station, Texas, 16-18 May 1988, pp. 415-430.

Correction

The June 1993 Orbit contained an error. The article, Plus and Minus Spectrum, on page 16 repeated the same Spectrum plot for Figure 4, examples 1-5. The amplitude, speed, dates and times of the Spectrum plots should have corresponded to the Orbit/Timesbase plots displayed. We regret any confusion this may have caused. ■

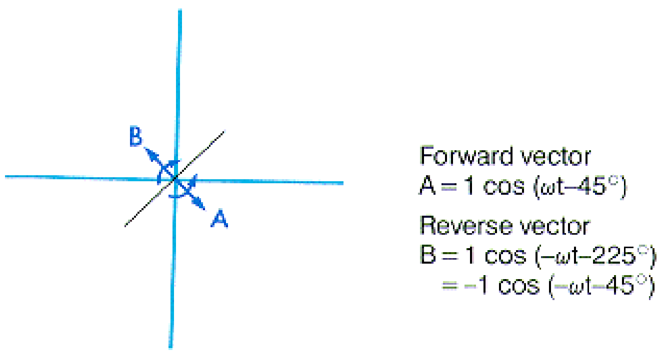

Figure 6

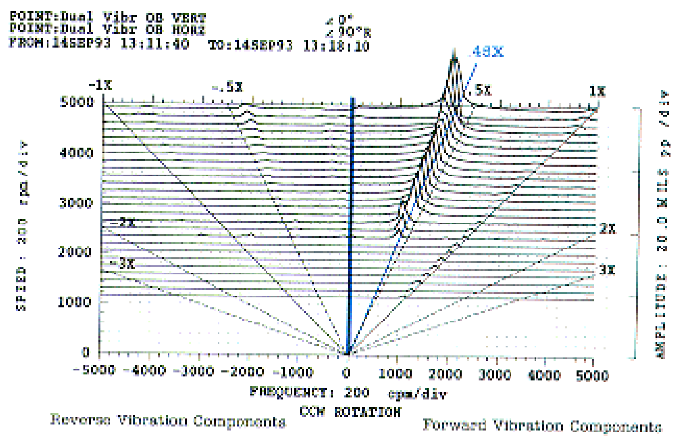

Figure 7
Fluid-induced instability

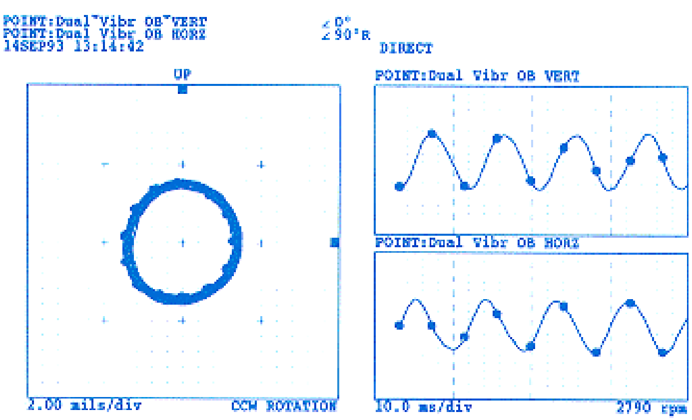

Figure 8
Fluid-induced instability: oil whirl produces a circular, or nearly circular, orbit with forward precession (2790 rpm).

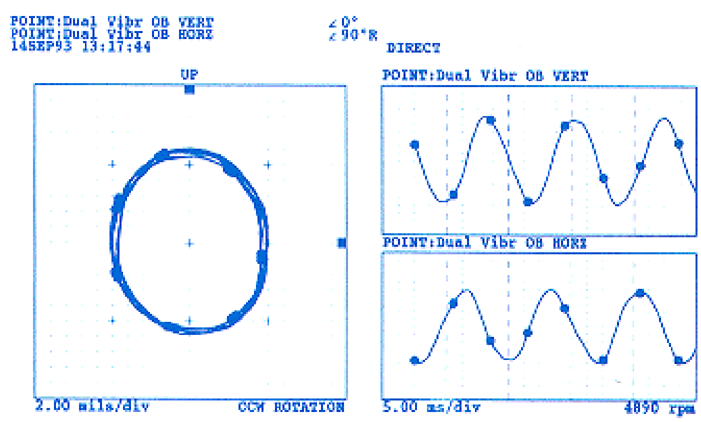

Figure 9
Fluid-induced instability: oil whip produces a circular, or nearly circular, orbit with forward precession (4890 rpm).